Robot work crews for planetary outposts:
close cooperation and coordination of multiple mobile robots

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ABSTRACT

We report on the development of cooperating multiple robots. This work builds from our earlier research on autonomous planetary rovers and robot arms. Here, we seek to closely coordinate the mobility and manipulation of multiple robots to perform site construction operations--as an example, the autonomous deployment of a planetary power station--a task viewed as essential to a sustained robotic presence and human habitation on Mars. There are numerous technical challenges; these include the mobile handling of extended objects, as well as cooperative transport/navigation of such objects over natural, unpredictable terrain. We describe an extensible system concept, related simulations, a hardware implementation, and preliminary experimental results. In support of this work we have developed an enabling hybrid control architecture wherein multi-robot mobility and sensor-based controls are derived as group compositions and coordination of more basic behaviors under a task-level multi-agent planner. We summarize this Control Architecture for Multi-robot Planetary Outposts (*CAMPOUT*), and its application to physical experiments where two rovers carry an extended payload over natural terrain.

Keywords: mobile robots, cooperating robots, robot control architecture, sensor fusion, intelligent control, Mars exploration, Mars rovers, robot outposts, field robotics, mobile manipulation, robotic navigation, ***SRR*** (Sample Return Rover)

1. INTRODUCTION

Figure 1. Two robot cooperative transport scenario

The current focus of Mars exploration includes remote science by robotic landers, autonomous rovers, and/or other surface and subsurface-based assets, leading to a future Mars Sample Return. In the longer term, robotic exploration of Mars will likely entail cooperative activity of multiple robots [17]. These cooperating robots will work as "crews" of coordinated intelligent agents, carrying out site preparations, site maintenance functions, and remote science investigations, eventually in partnership with human co-habitants of such planetary outposts. We report the preliminary development and experimentation with such robotic system concepts, building on prior JPL work in autonomous planetary rovers and robots, e.g., our recent development of the MarsArm, LSR, SRR, FIDO platforms et al. [1-3]. Our new research focuses on definition of cooperating robots that can coordinate closely and continuously to perform a site construction task, as depicted in both **Figures 1** and **2**—the autonomous deployment of a solar photo-voltaic (PV) tent array. Such a Mars power station is an essential precursor to long duration robotic or human presence, viz. planetary outpost. There are numerous challenges in this prototypical task; problems include the cooperative manipulative acquisition of extended objects from a container storage depot, the cooperative transport of such a container to the power array construction site, and the physical deployment of the container into the array. Two features of this scenario are particularly salient in our ongoing work, which emphasizes the *"transport phase"* (Figure 1**)**: 1) cooperative sensor-based autonomous traverse of two kinematically linked rovers across natural, uncertain terrain; 2) distributed force-motion control of this non-holonomic extended platform (each rover having a gimbal-mounted gripper that is instrumented for force-position in all axes, and compliance in one). We have developed a tiered behavior control architecture for closely coupled operation of multiple robots, wherein mobility and control functions are derived as group compositions and coordination of more basic behaviors under the downward task decomposition of a multi-agent planner. The architecture is extensible and scales freely with regard to behavioral mechanisms and protocols it can host and fuse, re-mappable inter-robot communications (for both implicit and explicit networking) it can support, and the overall ability to functionally integrate heterogeneous, multi-purpose platforms. We report on this Control Architecture for Multi-robot Planetary Outposts (***CAMPOUT***), some supporting simulations, and physical experimentation to date with two rovers carrying a model payload over natural terrain. *Section 2* outlines the system concept and research background; *Section 3* overviews our control architecture and related software simulations; *Section 4* briefly describes some physical experimental results. See also our companion paper [4] of this meeting which provides a more detailed report of the CAMPOUT design strategy, features, and early implementation results.

2. SYSTEM CONCEPT

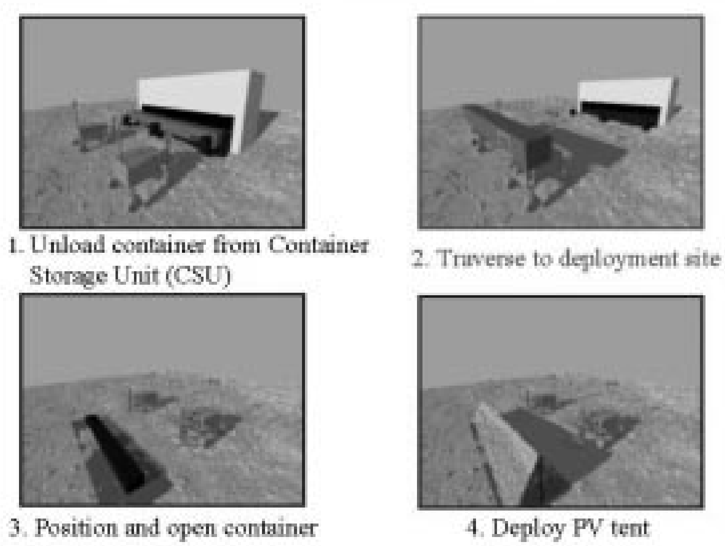


Figure 2. Concept for deployment of a Mars PV tent power station, showing key payload acquisition, transport, and deployment phases

Robotic outposts, as based in *robot work crews* (**RWC**), will require close integration of mechanical subsystems, rich multi-sensory data streams, and networked control architectures. Such an outpost will, by definition, be a collection of evolving heterogeneous robotic platforms, under frequently varying control and communications protocols due to the wide range of tasks (some unforeseeable) that they will be required to do. The control architecture must therefore not be a "point design," but rather, extensible and expandable. Tasks may include not only site preparation and maintenance functions, but also support of science goals (instrument deployments, sample transport, in-field rendezvous, etc.). A key requirement for a robotic outpost is capability to manipulate/transport extended structural elements necessary for construction and maintenance tasks. These elements will be of a size that is not easily handled by a single mobile platform. For example, the container length for a single element of a photovoltaic tent array is projected to be 5 meters [5].

Recently, robotics researchers have investigated transportation of large extended objects based in autonomous cooperating or coordinated multiple robots (wherein the latter term, *coordinated*, infers tight coupling of the physical platforms' kinematics and possibly dynamical parameters). The emphasis of control architecture design underlying this work has been robust decentralized control schemes with limited state information exchange between robots. In most such configurations, each robot is compliantly linked to a gripper or compliantly coupled to a common payload. The decentralized control schemes take advantage of the locally sensed forces and moments exerted by the robots on the load to derive a control law to modify or generate new trajectories. In effect, the decentralized control schemes are compliant coordination schemes. Compliant control for multiple mobile robots is very different from that of a single mobile robot. First, the compliance frame is implicitly time varying, and second, the environment is not static because the contact occurs or is maintained while all robots are in motion. In general, we note that many approaches reported for cooperative robot motion do not generalize; they may not consider activity within a natural terrain, versus an idealized environment (lab floor), and/or fail to maintain an explicit continuous closed loop coordination of joint robot activities under physical constraints (rather, use time-sequenced, iterative actions of the independent robots to partially address global task constraints). Activities may be cooperative in a spatial sense, but not necessarily coordinated below a strategic level as to platform kinematics and inertial/dynamical interactions. In the more specific literature noted above, several researchers describe decentralized, somewhat monolithic control schemes for transportation of large objects using multiple mobile robots. Vinay et al. [6] presented simulation results of two mobile robots transporting a long object. Lagrange techniques were utilized to develop a state space model for two wheeled mobile robots compliantly coupled to a common payload. The system, via its use of state feedback control, was decoupled into five smaller subsystems, thus simplifying and facilitating the global controller design. Hisashi et al. [7] also presented simulation and experimental results of two cooperative mobile manipulators transporting a payload on an uneven ground. In the reported experiments, the robots and the payload consisted of three moving tables driven by ball screws. Mechanical compliance is archived by locking some of the joints of the manipulator and making the rest free. Simple joint position control laws are employed to accomplish compliant control between the mobile manipulators without the need for explicit communication.

Khatib et al. [8] proposed a somewhat more general decentralized cooperative control algorithm for multiple mobile manipulators using an augmented object and a virtual linkage model. The augmented object is used to describe the system's closed chain dynamics. The virtual link model is used to characterize and synthesis control laws for internal forces in a multi-arm systems. However, the algorithm requires an explicit and not always realistically achieved communication between the platforms. The experimental results presented demonstrate potential effectiveness of the control scheme.

Hara et al. [9] presented a cooperative transportation control scheme for two quadruped robots transporting a long payload. The quadruped robot locomotion is based on a vibration model in walking. A decentralized control scheme is developed based on a "leader-follower." Several experimental results are presented, such as transporting the load over stairs.

In reflecting on these developments and motivation for our own work, we note that previous studies of robotic requirements for Mars robotic outposts [10] indicate that increased levels of autonomy and more generalized payload handling capabilities than have been reported to date will be needed for habitat construction and surface infrastructure support on planetary surfaces. The applications challenge is further exacerbated by the facts that the planetary surface environment is very unstructured (often unpredictable with respect to both character of perceptual artifacts and poorly modeled nature of vehicle-surface interactions) and such missions will be of extended duration and changing goals/priorities. A generalized *behavior-based control*, as described next, appears to offer a practical level of flexibility, autonomy, and computational economy [11, 12] for preliminary design of such space-targeted technologies and systems.

3. SYSTEM ARCHITECTURE & CONTROL SIMULATION

In this section we overview our hierarchical control and data constructs for implementing a closely coupled cooperation between multiple robots—***CAMPOUT*** (Control Architecture for Multi-Robot Planetary Outposts). CAMPOUT is a *hybrid reactive/deliberative architecture* incorporating higher-level constructs for the task-level planning/decomposition of activities under finite resource and goal constraints and the lower level composition, coordination, and sequencing of behaviors for reactive control in tight perception-action feedback loops. We also describe some related work on lower-level control simulations that enable us to validate various supporting controller designs prior to committing them to a real-time software or/and hardware implementation.

3.1 System Architecture

For control and coordination of the activities of two crew robots in the task of collective retrieval, transport, and final deployment, we have developed a control architecture that brings together ideas from various existing architectures [4]. Most important, this new architecture provides facilities that enable a close sensor-based coordination among physically constrained robots. The architecture is by no means limited to robot servicing activities by homogenous agents. Rather, CAMPOUT is a rich and general framework for task-level control and coordination of a set of arbitrary heterogeneous telerobots, scaling well with both task and system complexity. CAMPOUT provides a structured approach to design, specification, implementation and validation of a complex control system and its subsystems. CAMPOUT is based on a behavioral paradigm [16] for hierarchically integrating a modular set of action-producing modules called behaviors and imposes constraints that guide the way the control problem can be solved. **Figure 3** gives a high-level overview of the control architecture, but does not and cannot represent the whole architecture [4].

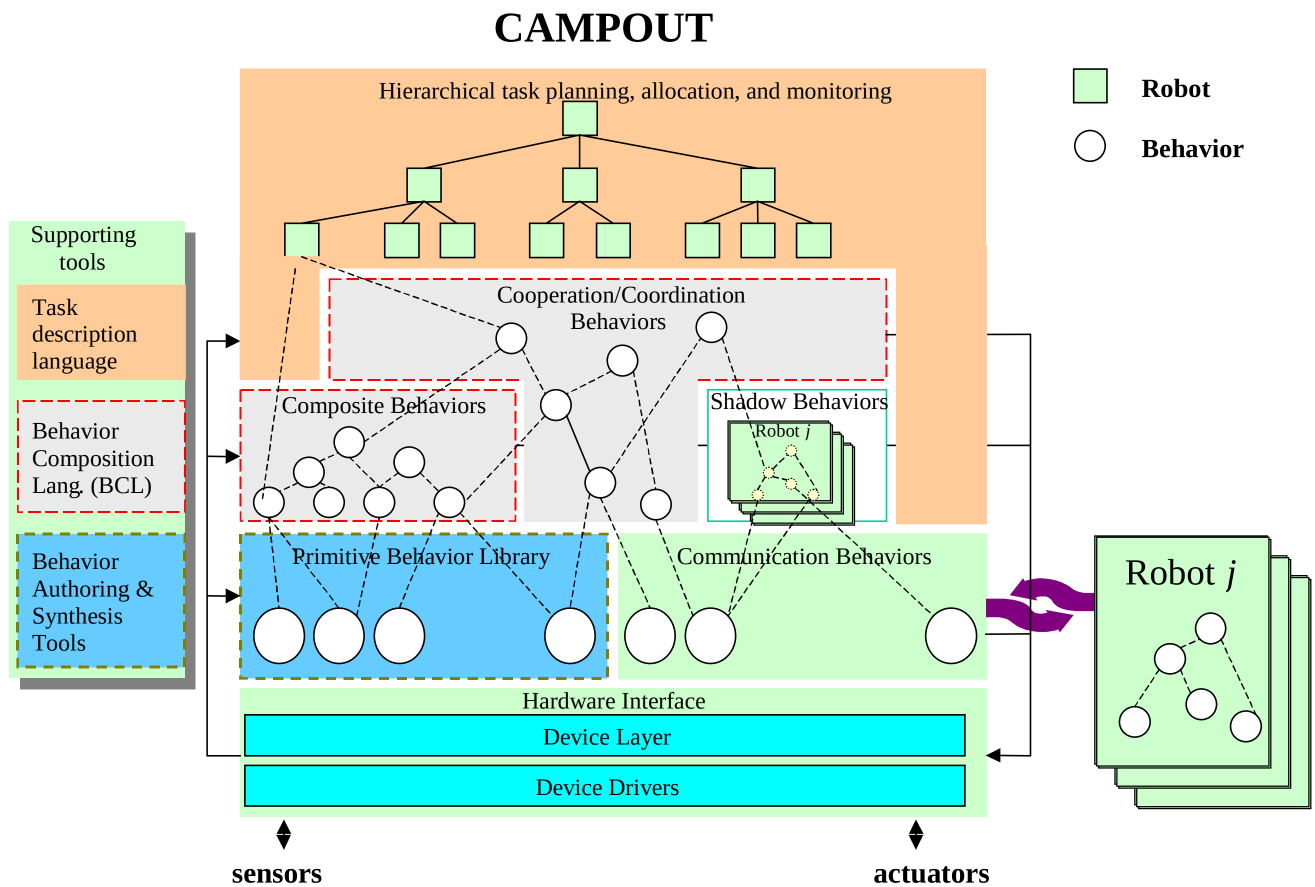


Figure 3. A logical block diagram of the Control Architecture for Multi-Robot Planetary Outposts (*CAMPOUT*)--its components, interaction between components, interfaces, and tools

Due to the technology focus and near term demonstration objectives of our work, we have yet not integrated a planner into the architecture. At this time, emphasis is on the behavior control paradigm and its coordinated multi-robot implementation. The following is a brief description of the main characteristics of CAMPOUT, see [4] for further details:

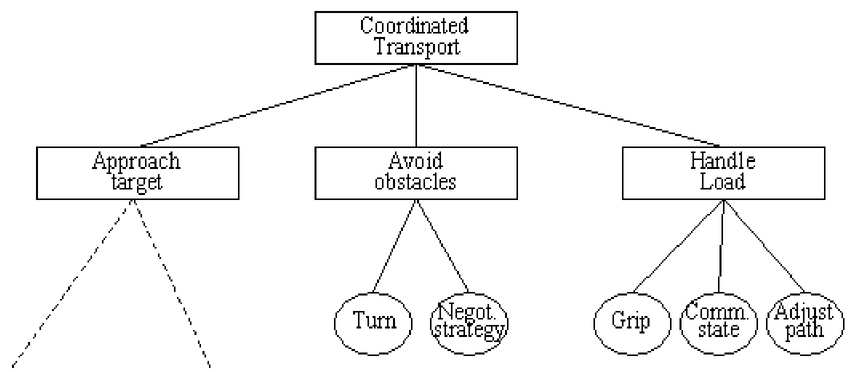
- **Hybrid**: The architecture that we propose is characterized as "hybrid" within the realm of current behavior-based approaches to robot control [16]. Hybrid architectures are viewed to provide the most general type of control due to their combining low-level reactive components with high-level deliberative planners.
- **Behavior-based:** Due to its generality and demonstrated success to date, a hierarchical behavior-based paradigm was chosen as the focus for our design of reactive/real-time cooperative controls; this appears a realistic starting point for the computation-and-memory constrained environment of space robotics. While a behavior-based approach is best suited to implementing lower-level reactive aspects of an architecture, the above-noted layering of planning over a behavioral level of control is gaining more acceptance within the behavior-based system design community.
- **Distributed:** The approach we are proposing is highly distributed. First, behaviors within a single robot operate in a distributed manner thus allowing for concurrent and/or parallel execution of several tasks. Second, each robot can operate on its own, independently of other robots, based on its embedded faculties of perception and action. Cooperation between multiple robots occurs through active collaboration, *with no centralized planning or decision-making component to dictate explicit commands*. The advantages of such truly distributed control and coordination include: efficient use of system resources, parallel execution of multiple tasks, reliability and fault-tolerance to failure of individual components (including the failure of a single robot or more at large).

Apart from this philosophical design framework, CAMPOUT provides a broad-based set of supporting developmental tools:

1. **communications infrastructure** for information exchange between system components/robots, sharing of information (e.g., sensory data) across robots, and for behavior coordination across a network of robots
2. **facilities for construction of behaviors** (a fuzzy inference engine is provided for rapid prototyping of behaviors)
3. **behavior coordination mechanisms** (see Pirjanian [13, 14] for an overview) for behavior arbitration and command fusion between inter- and intra-robot behaviors
4. **support tools** for interactive test and monitoring of system state.

The two main behaviors that are being used for the coordinated transport task are *Coordinated Transport*, a group behavior that autonomously controls the system between the container storage standoff position and the staging area, and the *Assume Transport Formation*, a group behavior that autonomously guides the two rovers into a specific formation such as *row* (side-by-side) or *column* (leader-follower). The hierarchies for these two group behaviors are shown in **Figure 4** and **Figure 5** respectively. Overall control of the entire four-phase sequence is through a plan that has been encoded as an 11-step finite state machine (FSM). Navigation is based on fusion of information from the sun-sensor, odometry, and stereo mast cameras. Arrival at the staging area is determined by the use of visual landmarks and odometry.

Figure 4. *Coordinated Transport* group behavior hierarchy that uses behavior fusion at the root level. This behavior is responsible for maintaining a heading toward the deployment point while at the same time avoiding obstacles and not dropping the extended container.



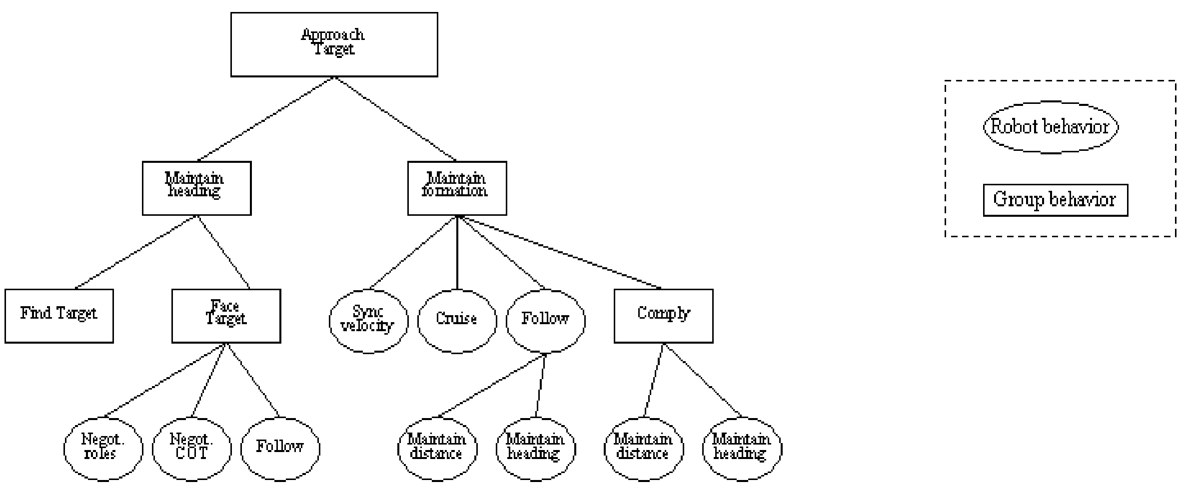
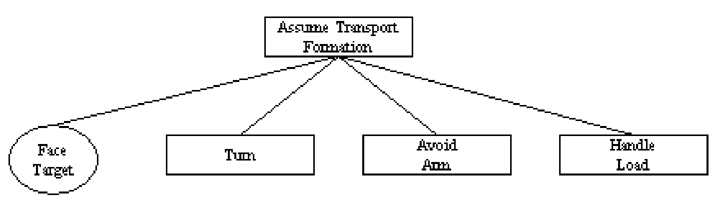


Figure 5. *Assume Transport* group formation that uses behavior fusion at the root level. This behavior is responsible for arranging the rovers in a specified formation while at the same time handling the load through coordinated rovers.



The behavior fusion method used is the *multiple objective behavior control* (MOBC) framework developed by Pirjanian [13, 14]. This framework uses the outputs of the lower level behaviors to select the behavior that satisfies possibly conflicting actions (a concept called “satisficing action selection”).

3.2 Control Simulation

In parallel with actual hardware and software development, a dynamics and control simulator has been developed and utilized to prototype, test and verify control algorithms prior to their implementation on the physical system. This allows conceptual studies to be undertaken to explore issues related to the control of coordinated rover systems [15]. The simulator is implemented within the *Matlab/Simulink*™ software environment. This software environment was chosen for its ability to initially model the rover system with simplifying assumptions and then later increase the fidelity of the simulation by relaxing assumptions as required. The simulation is built around a hierarchical framework wherein the bottom-most level consists of basic rover dynamics. Higher levels above incorporate individual rover friction models and low-level, individual-rover controllers. The next higher levels incorporate beam dynamics and higher level planning and control functions.

The simulation to date consists of test-validated models of two closely interacting rovers, including dynamics of the rovers, low-level controllers (and associated low-level trajectory generators), noise models for terrain variation and sensor uncertainty, and a quasi-static force model of a stiff beam. As the simulation was built after *individual* low-level controllers had already been implemented on our experimental vehicles (cf. later SRR vehicle description), the simulation used the same controllers and low-level trajectory generators. Test data was collected from the actual rovers to validate individual-rover simulations. A noise filter was incorporated into the models to simulate velocity profiles perturbed by terrain variations. A simple quasi-static force model of a stiff beam was implemented to model the physical interaction between the rovers. A model of the effect of the beam-interaction force on the rover was also implemented by having it influence the rover forward and transverse velocities. The top-level display of the Simulink™ model is shown in **Figure 6**.

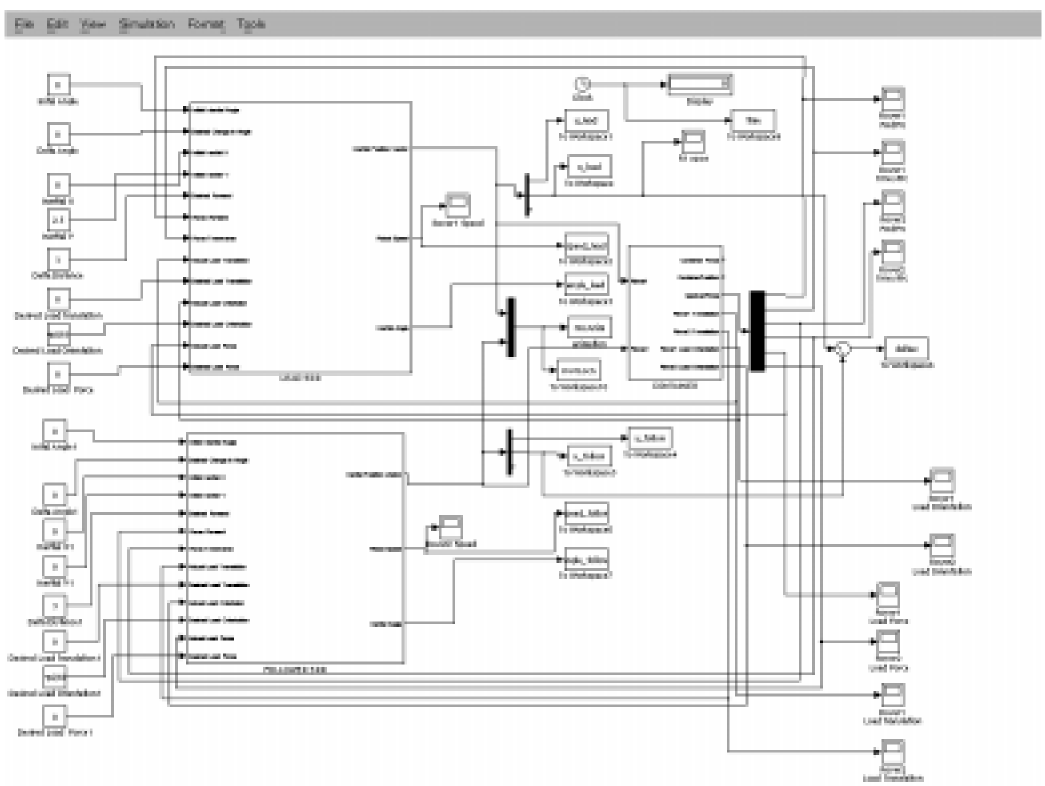


Figure 6. Top-level model of control simulation

Above the low-level rover position and velocity control layer of the simulated system architecture, there is a set of control loops based on locally acquired sensor readings; this controller is used to modify commanded rover velocity. The control loops within were first implemented in simulation to optimize control gains and test control-loop output combination strategies. In the physical system, the sensor readings used in these control loops are from a gimbal that is mounted on the rover and used to hold the beam. The instrumented gimbal provides potentiometer-sensed readings of its local gimbal yaw, pitch, roll, translation and 6-axes interaction forces, with position accommodation along the beam axis proper. Models of these sensors were used in the simulator to provide data for the control loops. Three loops were implemented:

- yaw control to maintain orientation of each rover with respect to the beam,
- translation control (to keep the beam grippers at the mid-point in their range of travel)
- beam force control (to maintain a desired force in the beam compression/extension force

The outputs of these three control loops were weighted and combined as shown in **Figure 7** and used to influence the local rover (either increase or decrease) velocity.

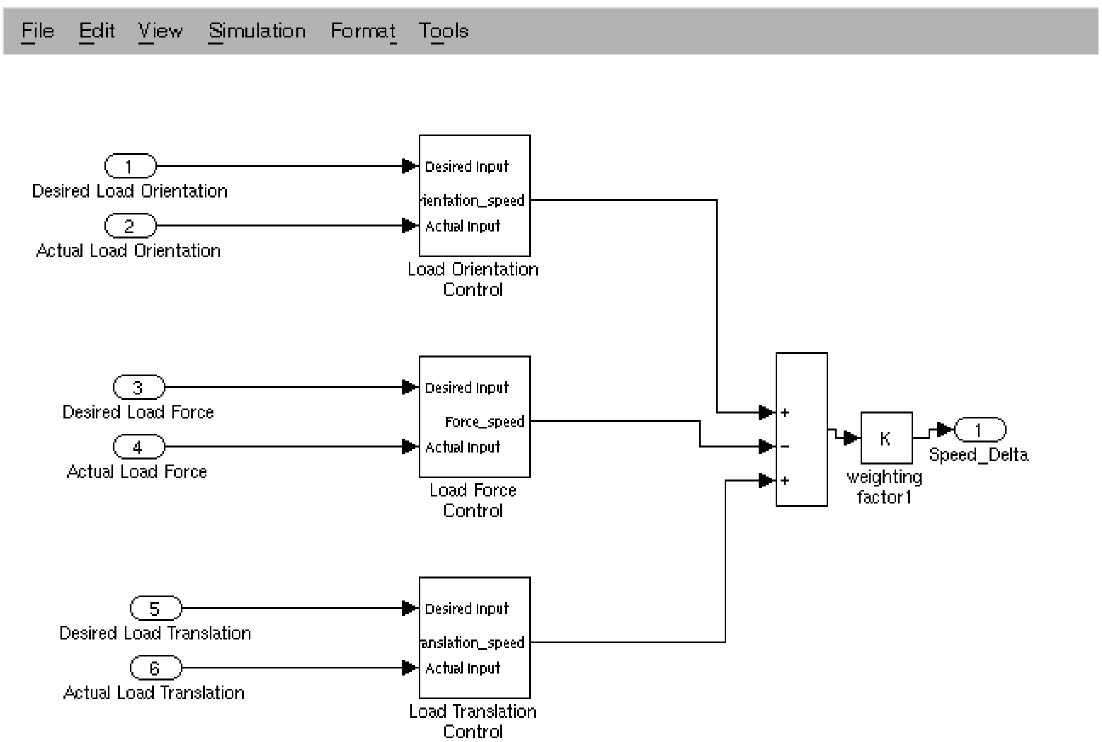
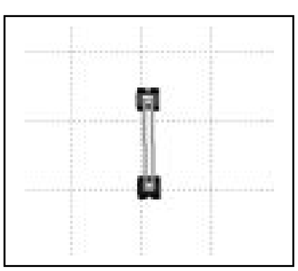


Figure 7. Example of the combination of outputs of the three control loops



Output from the Simulink model was displayed as numerical values on the Simulink display and plots of the variables of interest against time, also as a two-dimensional animated display—a top view of the rovers connected by a beam, as seen in **Figure 8** at left.

Figure 8. Two-dimensional display showing top view of two rovers connected by the beam

A number of simulations of this model were run with varying parameters, before we proceeded to implementation on the actual system. An example of the output velocity profile for a rover during a simulated three meter traverse is shown in **Figure 9**. The random signal superimposed over the steady state 0.06 m/s velocity signal is the rover response to a terrain noise model introduced in the simulation.

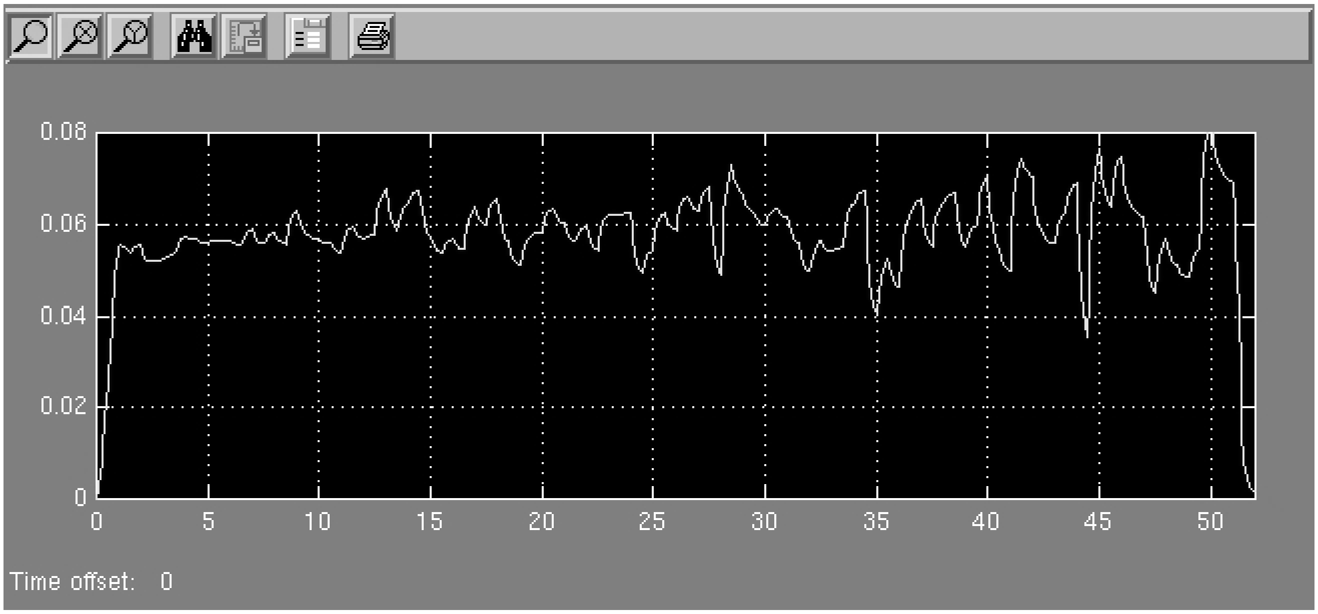


Figure 9. “Follower-rover” velocity profile (cf. “leader-follower” and column transport, Figure 10, below)

The results from the simulations verified that the control approach was feasible. The algorithm and parameter values from the simulation were used as an initial configuration in designing corresponding behaviors for the two-rover system next described.

4. SYSTEM IMPLEMENTATION & EXPERIMENTATION

Objects that are four to five times the length of a single mobile platform are extremely difficult to manipulate and transport. The ***Robot Work Crew (RWC)*** concept assumes multiple rovers for coordinated operations on such a payload. Examples of *row* and *column* transport are shown in **Figure 10**, wherein two rovers share the handling of an extended, stiff object.

Figure 10. Coordinated transport of an extended container (2.5 m) by SRR and SRR2K
Left: row transport formation; *Right*: column transport formation

These closely coordinated multi-robot operations are implemented using small autonomous rovers that have evolved from our recent work on planetary science exploration and sample return. The baseline rover design, the ***Sample Return Rover*** **(SRR)**, is reported in [2, Schenker], wherein it incorporated skid steering and a basic functionalities for stereo-based obstacle detection, continuous motion visual traverse (10+ cm/sec), visually-servoed manipulation, and in-field visual object detection, tracking, and rendezvous. More recently, as summarized in **Figure 11**, we have augmented the rover with 4-wheel steering, improved computational resources, the CAMPOUT behavioral control architecture, and instrumented gimbaled grippers.

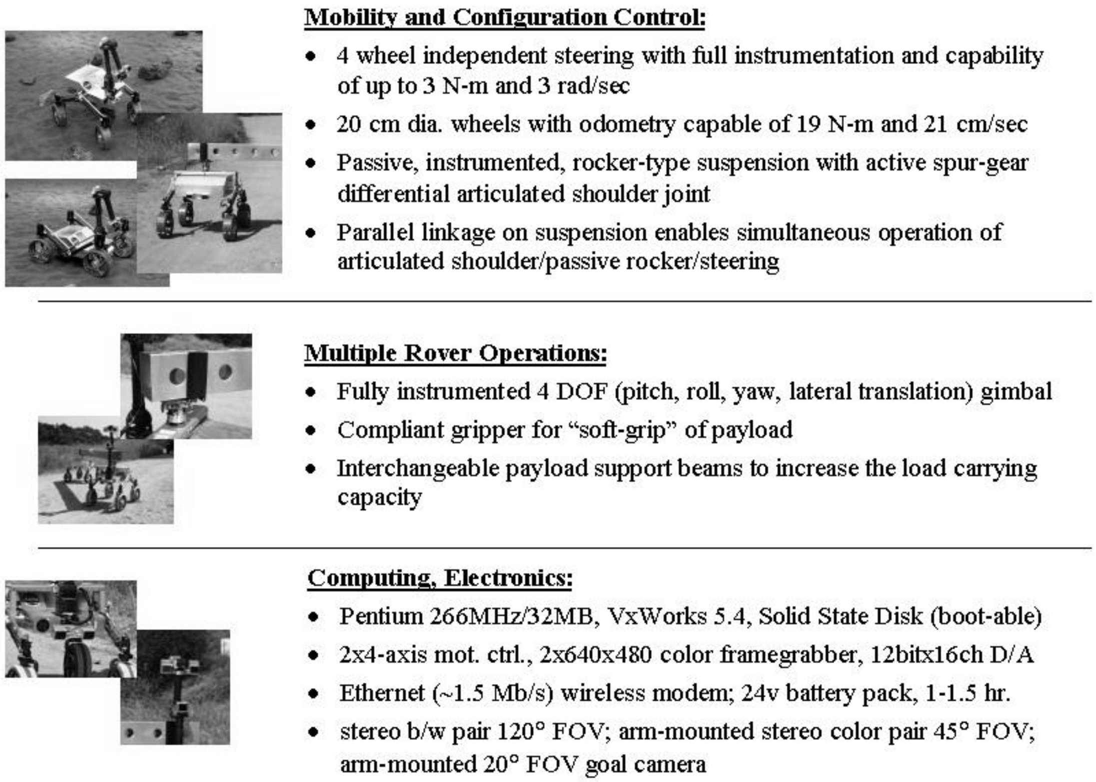
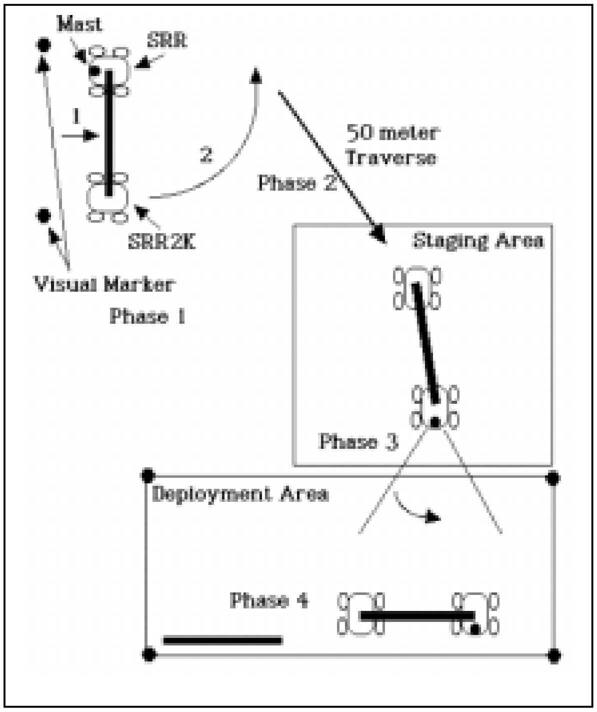


Figure 11. Summary of some JPL *Sample Return Rover* (***SRR***) features relevant to RWC operations

A fully actuated approach to the transport of extended structures may not be realistic for planetary surface operations due to mass and power restrictions. In order to determine minimal requirements, we initially are investigating a fully instrumented, passive gimbal design shown in **Figure 12**. The gimbal is attached to a cross brace that spans the shoulders of the SRR and has 3 DOF force sensors and pots for monitoring the movement of the container relative to the rover body. In order to minimize explicit communication between the rovers, these sensors are used as an implicit link for rover coordination. Our goal for the experimental study is the transport of an extended container (12.5cm X 12.5cm X 250.0cm) by two rovers (SRR and SRR2K, the latter being a minimalist mechanization of the first) from a pickup point to a deployment zone that is up to 50 meters away over relatively benign terrain. This is to be accomplished with the four phase sequence shown in **Figure 13**: (1) *Initiate transport configuration*; (2) *Move to staging area*; (3) *Initiate site survey*; and, (4) *Dock into site.* Behavior-based control is utilized for this task at large, encompassing both single robot (primitive) and multi-robot (group) behaviors. See [4] for further details of the underlying control model.

Figure 12. Close-up of gimbal with container (simulated payload)



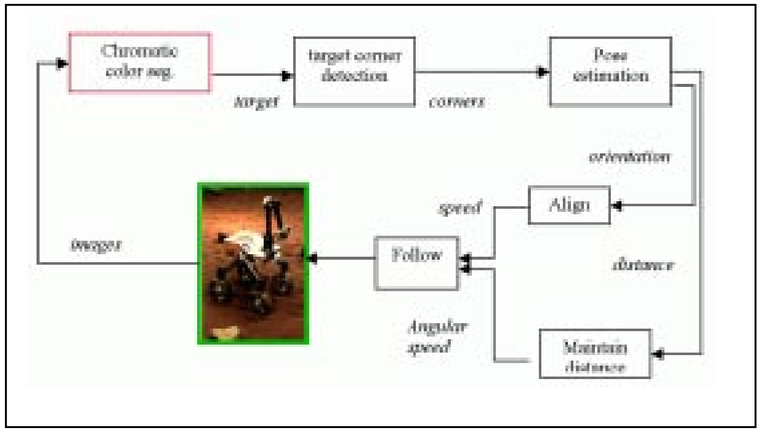


Figure 14 (above). Visual target detection is coupled with pose/ orientation estimation to maintain a constant distance and angular offset from a target.

Figure 13 (left). Four phase sequence for transport of an extended container from a central storage location to a deployment site up to 50 meters away

We illustrate the implementation of a "primitive behavior" in **Figure 14**; this is *Follow_Target* as utilized within the *Maintain Formation* "group behavior" of Figure 4. This primitive behavior supports maintenance of a specified formation via tracking of a visual marker at center of the extended container being carried between the two rovers. The marker is detected using color segmentation; corner features are found; and, the target's pose and orientation are calculated using the corner points. Because the marker's position relative to the extended container is known, relative positioning of the rovers can be inferred.

As a general implementation approach, we are currently attempting to minimize explicit communication between the rovers, as reflects possible operational constraints during an actual mission. This is facilitated by using the shared container as an implicit means of communication through the instrumentation on the gimbal (shown in Figure 12). E.g., the relative positions of the rovers are known through the yaw gimbal angle on each rover. Also, we are exploiting natural design constraints of the task where possible to assess useful trades of mechanized cooperation versus explicit control (as one example, use of passive compliance in both grippers along the beam axis). We will perform a hardware simulation of the complete two-rover transport scenario depicted in Figure 13 at the Arroyo Seco near Jet Propulsion Laboratory during September 2000.

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